Modelling and Control of Engine Torque for Short-Circuit Flow and EGR Evacuation

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Abstract

Low-Pressure Exhaust Gas Recirculation (LP-EGR) has been shown to be an effective means of improving fuel economy and suppressing knock in downsized, boosted, spark ignition engines. LP-EGR is particularly beneficial at low-speed, high-load conditions, but can lead to combustion instability at lower loads. The transport delays inherent in LP-EGR systems slow the reduction of intake manifold EGR concentrations during tip-out events, which may lead to excessive EGR concentrations at low load.

This paper explores leveraging Variable Valve Timing (VVT) as a means of improving the rate of reduction of intake manifold EGR concentration prior to tip-out. At higher boost levels, high valve overlap may result in intake manifold gas passing directly to the exhaust manifold. This short-circuiting behaviour could potentially improve EGR evacuation rates. However, introducing short-circuit flow may lead to lean exhaust flow through the catalyst, and/or necessitate rich in-cylinder conditions that could counteract the fuel economy benefits of increasing high load LP-EGR rates. Therefore, this paper seeks to quantify the improvement in EGR evacuation rate and duration of short circuiting that may be achieved while at boosted conditions with high valve overlap, in preparation for a tip out.

To conduct this investigation, a controller is first proposed, capable of regulating torque at boosted operating conditions with high valve overlap and external EGR. This controller extends a published control architecture, by accounting for both short-circuit flow and external EGR.

The developed controller is then applied to a GT-Power model to regulate torque during constant torque LP-EGR evacuations, where high valve overlap is shown to improve evacuation times by 15-25%.

Introduction

Cooled, external Exhaust Gas Recirculation (EGR) can be effective for improving fuel economy and for suppressing knock in turbocharged, spark ignition engines [1]. One approach for delivering external EGR is Low-Pressure (LP-)EGR, where exhaust gas is extracted downstream of the turbine and reintroduced upstream of the compressor (e.g. Figure 1).

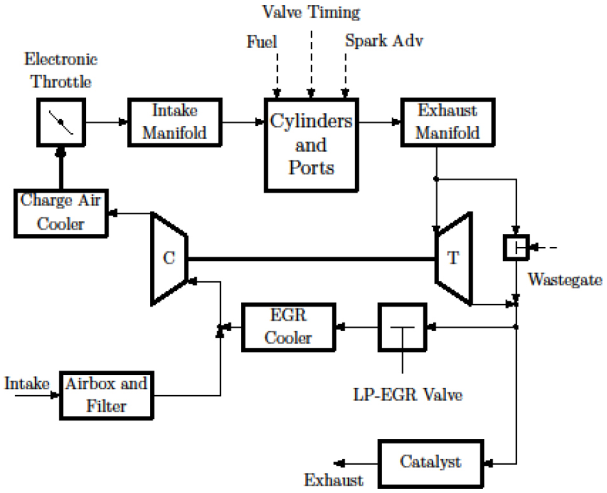

Figure 1. GT-Power simulation component diagram.

The efficacy of cooled, LP-EGR for knock suppression at low-speed and high-load is the subject of several published reviews (e.g. [1, 2, 3, 4]). These reviews highlight several inherent advantages of LP-EGR systems over high-pressure EGR systems, including the potential for higher EGR flows due to favourable pressure gradients [1, 2], better cylinder-to-cylinder distribution [4], lower heat rejection requirements for the EGR cooler [2], and the ability to leverage the charge air cooler to assist in heat rejection [4].

Despite these advantages, LP-EGR is limited by the transport delay in the path between the LP-EGR valve and the intake manifold. Slow EGR response is of particular concern during tip-out events, as lower external EGR tolerance at low load conditions may lead to unacceptably slow combustion rates. This effectively constrains the maximum LP-EGR rate that can be sustained at high load, prior to a tip-out.

This paper presents a feasibility study into relaxing this constraint on the maximum LP-EGR rate, by reducing the LP-EGR concentration in the intake manifold immediately prior to a tip-out. Specifically, the study examines the potential benefit of leveraging Variable Valve Timing (VVT) to shorten this evacuation process by introducing valve overlap at boosted conditions to increase scavenging [5].

At the low-speed, high-load conditions that are of interest for LP-EGR, high valve overlap results in intake manifold gases passing directly to the exhaust manifold (or 'short-circuiting') across the cylinder without participating in combustion events [5]. This phenomenon may be beneficial for decreasing intake manifold EGR concentrations by passing external EGR directly to the exhaust manifold. However, this short-circuit flow may lead to rich exhaust flow through the catalyst, adversely affecting catalyst performance. To counteract this, it is possible to maintain stoichiometric conditions in the exhaust by introducing rich combustion in the cylinder. While this would restore catalyst performance, it may increase catalyst temperatures [5] and lead to increased fuel consumption, potentially negating the benefits of increasing the EGR concentration. It is therefore desirable to quantify the required EGR evacuation period, and determine what improvement in EGR evacuation rate may be achieved through short-circuit flow.

As this 'short-circuit' behaviour only occurs at higher intake manifold pressures, it may also be beneficial to include a `preview' period, prior to decreasing the torque, allowing EGR evacuation to take place while the intake manifold pressure is still high. This preview may be facilitated through look-ahead information provided by vehicle telematics. In this paper, torque is constant during the preview period.

This study requires a controller capable of regulating torque given changing rates of external EGR, and changes in valve timing, particularly at operating conditions that induce short-circuit flow. Therefore, this paper first details an inversion approach to regulating torque. The controller structure is similar to that presented in [6], with extensions to account for operation with high valve overlap and external EGR. The resulting control law is derived from the inversion of torque and air charge models. This controller is demonstrated in simulation, and achieves acceptable torque regulation when applied to a representative, constant engine speed, VVT transient.

The developed controller is implemented to provide regulation during a preview period, in which engine speed is assumed constant, and the flow of LP-EGR is halted. LP-EGR evacuation times are compared with and without high valve overlap, and the impact of short-circuit flow on EGR evacuation rates is quantified.

GT-Power Model

This study is conducted in simulation, using a GT-Power [7] model of a turbocharged, direct-injection (DI), spark-ignition engine. A component-level diagram of the engine model is shown in Fig. 1. The engine incorporates dual-independent VVT and a cooled, LP-EGR circuit.

Throughout this study, the valve timings, as well as the LP-EGR valve position, are implemented as prescribed trajectories. For convenience, the intake and exhaust valve timings will be represented by the vector $\zeta_{cam} = [\zeta_{int}, \zeta_{exh}]$, noting that the valves are still considered dual-independent. The GT-Power model does not include a physical model of the cam dynamics, which are instead represented by a constant rate of change of cam phasing.

Spark timing is configured to achieve a desired combustion phasing, while the fuel flow ideally tracks a desired relative air-fuel ratio in the exhaust, λ_{exh}. It should be noted that in a DI engine, this value of λ_{exh} may vary from the in-cylinder value. When short-circuit flow is present, it leads to rich, in-cylinder conditions when maintaining stoichiometry in the exhaust [5]. Finally, the wastegate is managed using a Proportional-Integral control loop to track a desired boost pressure P_b.

With spark prescribed to achieve the desired combustion phasing, throttle is employed to control torque. The torque controller developed later in this paper assumes measurements of exhaust pressure P_e and EGR concentrations at the throttle inlet and in the intake manifold x_b and x_i respectively. These values are not typically measured on production, spark-ignition engines, but may be implemented using estimators (e.g. [8] for P_e) or sensors (e.g. intake air O_2 for x_i, x_b).

Control-Oriented Engine Model

The throttle controller described in this paper relies on steady-state models of the torque and air charge. Earlier VVT air charge models, such as [9], are limited to naturally aspirated conditions, and do not account for short-circuit flow phenomena. When addressing high valve overlap (e.g. [10] for diesel engines, and [11] for spark ignition engines), the effect of exhaust pressure on flow and trapped mass at high valve overlap needs to be considered. As the model presented in [11] is not invertible (and therefore not suitable for the throttle control proposed in the paper), an invertible model accounting for exhaust pressure and external EGR is outlined below.

For this study, *BMEP* is modelled by curve-fits to flow-sweep data obtained from the GT-Power model

$$BMEP = H\left(m_{air,tr}, N_{eng}, \zeta_{cam}\right), \tag{1}$$

where $m_{air,tr}$ is the trapped mass of air in the cylinder and N_{eng} is the engine speed. Complete mapping of torque for a turbocharged engine with dual-independent VVT and external EGR involves a significant number of independent actuators. To reduce the number of actuator sweeps that need to be performed, it is assumed that steady-state spark timing and λ_{exh} are not independent variables, but are instead scheduled according to engine speed and torque. It is further assumed that a regression from flow sweep data obtained at $x_i = 0$ is sufficiently accurate for cases with $x_i \neq 0$.

For this paper, the combination of fresh air and external EGR is indicated by the subscript *mix*, such that the mixed trapped mass is defined as

$$m_{air,tr} = m_{mix,tr}(1 - x_i). \tag{2}$$

For engine operating conditions where short-circuit flow does not occur, the mixed, trapped mass is the net flow past the intake valves into the cylinder. Under these conditions, $m_{mix,tr}$ is a scalar multiple of the cycle averaged, mixed cylinder flow rate, $W_{mix,cyl}$. However, for engines operating with high valve overlap, some of the cylinder flow $W_{mix,cyl}$ may pass directly to the exhaust manifold. The fraction of $W_{mix,cyl}$ that is trapped in the cylinder is dependent on intake (P_i) and exhaust pressure [5],

$$m_{mix,tr} = M'\left(N_{eng}, \zeta_{cam}, W_{mix,cyl}, P_i, P_e\right). \tag{3}$$

Previous works concerning air-charge modelling and control (e.g. [9]) have represented the flow past the intake valves as an affine function of P_i for cases with low valve overlap. However, as for $m_{mix,tr}$, $W_{mix,cyl}$ also becomes dependent on P_e at high valve overlap. Therefore,

$$W_{mix,cyl} = F\left(N_{eng}, \zeta_{cam}, P_i, P_e\right). \tag{4}$$

Both the control-oriented and GT-Power models assume instantaneous, perfect mixing within the manifold.

Torque Inversion Control

This section describes a torque control developed to meet a desired *BMEP* request, considering high valve overlap at boosted operating conditions and external EGR. The controller is modelled after [6], where a target torque or *BMEP* is translated into a desired air mass. The desired air mass is used to determine a desired intake manifold pressure, which may then be used to calculate a reference throttle angle θ_0. The controller presented here extends this structure by accounting for EGR and short-circuit flow. A block diagram corresponding to this controller is presented in Fig. 2.

This structure is comprised of four discrete steps, beginning with the current ζ_{cam}, N_{eng} and a desired $BMEP^*$,

Step 1

Translate $BMEP^*$ to a desired trapped mass of air, $m^*_{air,tr}$ by inverting (1)

$$m^*_{air,tr} = H^{-1}\left(BMEP, N_{eng}, \zeta_{cam}\right), \tag{5}$$

Step 2

Convert $m^*_{air,tr}$ to a desired mixed trapped mass $m^*_{mix,tr}$

$$m^*_{mix,tr} = \frac{m^*_{air,tr}}{(1 - x_i)}, \tag{6}$$

Step 3

Calculate a desired intake manifold pressure P_i^* from $m^*_{mix,tr}$. Given measurements of ζ_{cam} and a measurement or estimate of P_e, (3) becomes a function of two unknowns, $W_{mix,cyl}$ and P_i. By substituting (4) into (3), a function for the $m_{mix,tr}$ in terms of P_i is obtained

$$m_{mix,tr} = M\left(N_{eng}, \zeta_{cam}, P_i, P_e\right) \tag{7}$$

Equation (7) is then inverted to obtain

$$P_i^* = M^{-1}\left(N_{eng}, \zeta_{cam}, m^*_{mix,tr}, P_e\right), \tag{8}$$

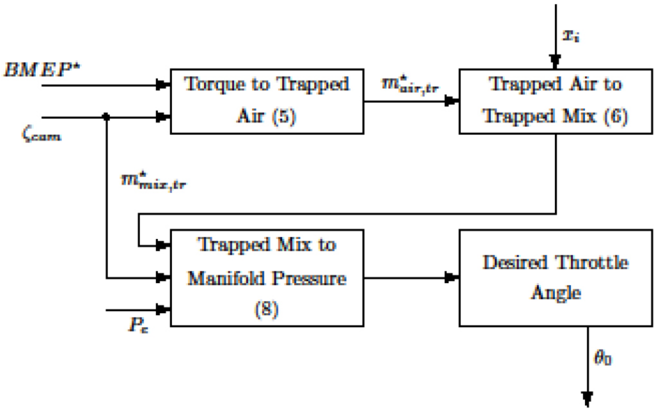

Figure 2. Torque control block diagram

Step 4

Determine a reference throttle angle θ_0 that delivers P_i^*.

To evaluate the performance of this controller for *BMEP* regulation, Steps 1-4 are implemented in the GT-Power engine model. Figure 3 shows selected actuator and output traces for a transition from a low valve overlap condition to a high valve overlap condition ($\zeta_{cam} = \max(\zeta_{cam})$) and then back to the low overlap condition, at constant engine speed while attempting to maintain a constant *BMEP* output.

For this representative case, the torque controller is shown to be capable of regulating *BMEP* to within 3.1% of the desired value. Figure 3 also indicates asymmetric dynamics during the VVT transients. For both valve timing transients, the actual intake manifold pressure is higher than the desired value for the period of transient *BMEP* deviation. However, in the first transient, this leads to undershooting the desired trapped mass, and overshooting the desired mass in the second. Given the imperfect nature of the regressions, it is difficult to isolate the source of this behavior, although it is reasonable to expect that asymmetric exhaust pressure behavior would be a contributing factor.

The performance of this controller is considered acceptable for the current application. The controller could be further refined by adjusting the commanded throttle position to compensate for the change in VVT phasing (c.f. [12, 13]). However, given the acceptable performance of the controller, such refinements are not expected to substantially influence the EGR evacuation results, and are not considered in this paper.

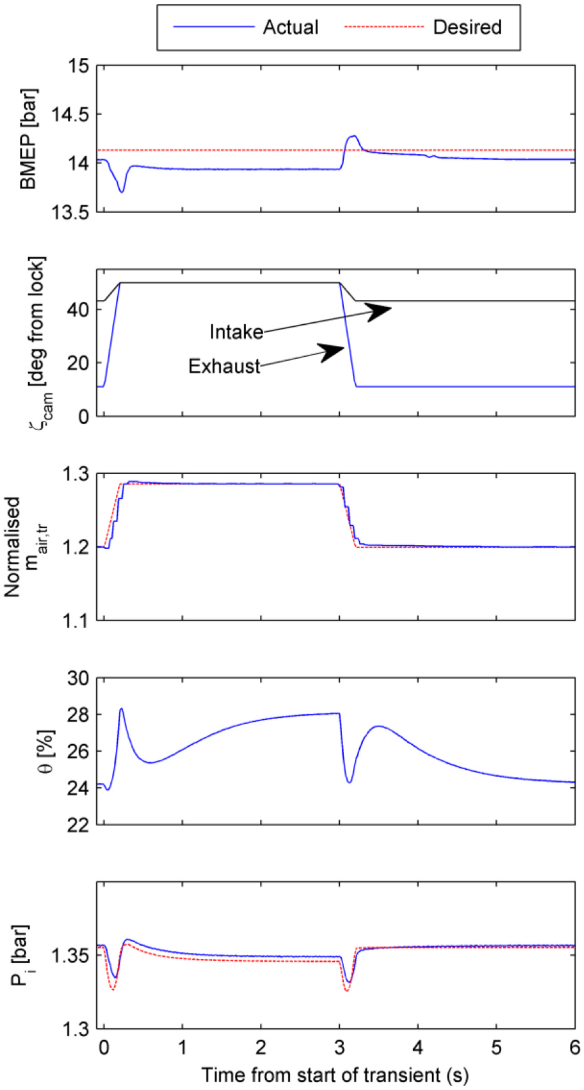

Figure 3. Simulation traces for BMEP regulation during VVT transient at 2000rpm.

EGR Evacuation

The throttle controller in Fig. 2 is now employed, in order to quantify potential improvement in external EGR evacuation times during a constant torque, preview period. These simulations assume constant engine speed, and begin with an initial, non-zero concentration of external EGR in the intake manifold. At the beginning of the preview period, the LP-EGR valve is instantaneously closed, initiating the evacuation process. For the first set of simulations, the valve timing is fixed, and the time taken for the EGR concentration in the intake manifold to reach 10% of the initial value is recorded. In the second set of simulations, the first set of simulations is repeated with the valve timings changing to maximum overlap, beginning when the LP-EGR valve is closed. The simulation traces for one representative case (N_{eng} = 2000 rpm, $BMEP^*$ = 14.1 bar) are plotted in Figs. 4a and 4b, and the summarised performance metrics for each of the operating conditions considered are presented in Table 1.

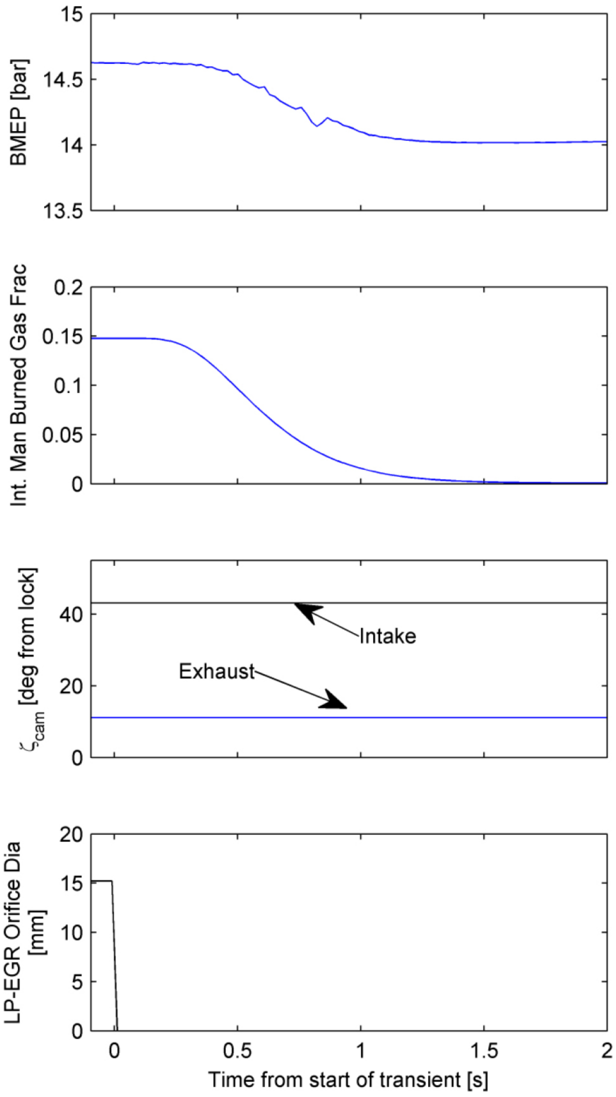

Figure 4a. EGR evacuation and BMEP regulation with fixed valve timing

For the results in Table 1, introducing high valve overlap, thereby inducing short-circuit flow, can reduce the EGR response time by 15-25% for the cases considered. This corresponds to a potential reduction of the preview period by up to 150 ms or 2.5 engine cycles.

In addition to quantifying evacuation rates, Figs. 4a and 4b also show the performance of the torque inversion controller for a scenario with external EGR. The controller exhibits minor steady-state error in the presence of external EGR, as the regression models were calibrated without external EGR. The steady-state regulation can be improved by including external EGR as an independent parameter when obtaining flow sweep data, at the expense of increased calibration effort.

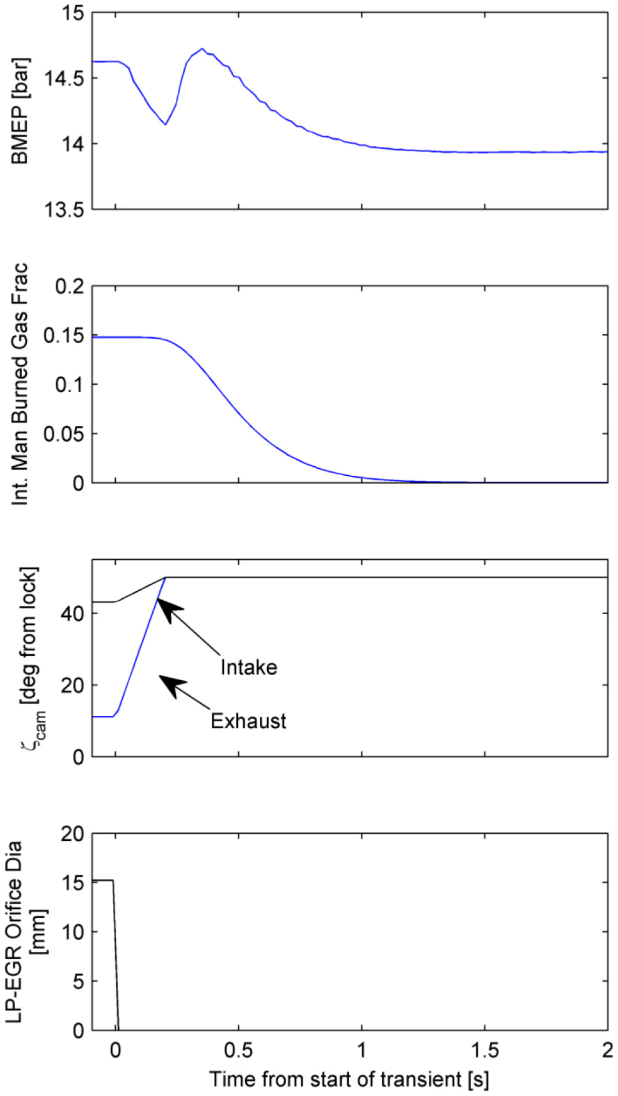

Figure 4b. EGR evacuation and BMEP regulation with high overlap valve timing

Table 1. EGR evacuation statistics

N_{eng}	$BMEP$	ζ_{cam}	Initial EGR	90-10% EGR response	Improvement in response
(rpm)	(bar)		(%)	(cycles)	(cycles)
2000	14.1	Fixed	15	10.3	
2000	14.1	High OL	15	8.8	1.5
2000	15.9	Fixed	10	10.3	
2000	15.9	High OL	10	7.8	2.5
1500	12.1	Fixed	10	14.0	
1500	12.1	High OL	10	10.7	3.3
1500	14	Fixed	10	11.1	
1500	14	High OL	10	8.1	3.0

Conclusions

This paper quantified the reduction in LP-EGR evacuation time that can be achieved during a constant torque preview period, immediately prior to a tip-out event. Performing this numerical study first required the development of a feed-forward throttle control, capable regulating torque while rejecting disturbances due to variable valve timing, external EGR and short-circuit flow.

This feed-forward throttle control was derived from torque and air charge models that incorporated external EGR and scavenging phenomena. A representative test case demonstrated BMEP regulation to within 3%, which was considered adequate for this investigation.

The developed controller enabled a series of engine simulations at different speeds and loads to measure the external EGR evacuation times for cases with and without valve overlap. These results suggested that preview periods in excess of 10 engine cycles would be required to evacuate 90% of the initial EGR concentration. Furthermore, the introduction of scavenging behaviour through high valve overlap was shown to reduce these evacuation times by ~1-3 engine cycles.

This investigation was conducted assuming that the near complete evacuation of external EGR is necessary before allowing the torque to decrease. In an actual engine, the LP-EGR tolerance at the beginning of a tip-out event will depend on the transient conditions as the torque decreases during the tip-out. To this end, future studies will focus on torque control and evacuation rates during the torque reduction component of a tip out event. A combination of the present and future approaches may then be used to develop a combined control approach capable of improving the maximum sustainable, LP-EGR rate at low-speed, high load conditions.

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